Markets 3.0 - The Impact on Market Behavior of Integrated Demand Side Resources

Ralph Masiello, Fellow, IEEE; Farnaz Farzan, Jessica Harrison, Kristie DeIuliis

Abstract -- Paper: Significant Penetrations of Price Elastic load and dispatchable demand response can introduce complex dynamics in the day ahead, hour ahead, and real time markets. This paper presents an analysis of conditions for market stability and illustrates them with realistic simulations of energy markets.

Index Terms -- *IEEE Smart Grid Innovative Technologies 2012*

I. Introduction

There are several strong drivers for the integration of demand side resources into energy markets and operations today. One is the development of various Smart Grid technologies and business models. The ability to manage demand at the end use level in reaction to market price signals and controls, promises to save consumers money, enhance grid operations, and make markets more efficient. Many smart grid projects are financially viable only when energy market impacts are estimated and considered in the overall cost-benefit equation.

The future scenarios of high penetrations of Variable Energy Resources (i.e. renewable resources such as wind and solar) has led to numerous studies of the impacts these will have on markets and operations. One consequence is an increased need for load following capabilities. This can be provided in several ways: increased use of fast responding conventional generation such as gas turbines and hydroelectric facilities; development and use of fast storage as a grid resource; and use of fast responding demand side resources to assist in grid operations.

There are multiple ways in which demand side resources can interact with the market. First is an autonomous response to a market price signal, or "Dynamic Pricing" (DP). Several appliance makers are developing smart appliances that can accept an energy price signal and control their on/off status or starting time accordingly. More complex local controls could include a Home Automation System that manages thermostat settings, air conditioner controls, and other loads against energy prices. In such schemes one question is "which price" do the resources follow – the day ahead (DA), Hour Ahead (HA), or intra hour (Real Time or RT) prices? Anticipating the dynamic response of such autonomous price sensitive load becomes a new dimension in load forecasting for market operators. Estimating potential demand elasticity has been of great interest in recent years as smart grid projects and technologies are anticipated.

A second way of interaction is for Demand Response to occur in response to control / dispatch signals from the market and system operator, or ISO. This kind of "Dispatchable Demand Response" or DDR makes DR look like a resource akin to conventional generation – it has to participate in various energy and ancillary markets and is paid a market price for responding to dispatch. FERC has recently issued Order 745 which spells out some principles of compensating Demand Response providers in the markets.

A third and more complex level of interaction is when the customer "self optimizes" energy usage over time in response to a schedule of market prices as in the case of day ahead hourly prices. This is one expected mode of microgrid operation and behavior – the microgrid operator looks at the published day ahead hourly prices and then schedules the microgrid production, storage, and demand resources during the day to optimize the financial outcome. In another variant the microgrid operator would bid some of those resources into the market as production or DDR resources as well. Sometimes this interaction is called a "Virtual Power Plant" or VPP; sometimes "microgrid" and sometimes "Self Optimizing Customer" or SOC. We will use the last form, "SOC.".

There are several questions of great interest to market operators and their communities around integrating DP, DDR, and SOC into market and grid operations. These include:

- How much of each kind of demand resource is likely to be available or to be developed in my markets?

- What are the technical and economic performance characteristics of these resources? What will the demand side "supply curve" look like? How fast can the DDR respond? Can it sustain response long enough to "fit" existing market products or are new product requirements in order to make best use of these resources?

- What will market behavior be like with these new kinds of demand side interactions? How do we manage market and system behavior in the presence of these new elements? At what levels of demand side penetration and with which types of interaction is market behavior affected?

- What levels of visibility and control are in order to integrate demand side resources? What level of certainty and magnitude of response is realized when the DR asset is called

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Kristie DeIuliis
Farnaz Farzan
Jessica Harrison
Ralph Masiello

upon? What technology roadmaps can be developed to monitor and control the different end uses in different applications? What is the cost-benefit analysis of monitoring and controlling demand side resources in the markets and grid operations overall?

This is one of several papers that describe recent and on-going efforts to answer these questions. Some recent projects have attempted to identify the potential of Demand Response by energy end use (as in HVAC, lighting, refrigeration, etc) and its technical characteristics. Some have examined the possible technology roadmaps for integrating demand resources. Some are examining the cost benefit equations around gaining visibility and control of demand resources. And some have looked at market dynamics and behavior when different demand side interactions are postulated.

This paper concentrates upon the market behavior question. It draws on results of projects that are examining the other questions but focuses on and develops answers to the questions posed above about market stability and how best to integrate DDR, DP, and SOC resources into the market. Some mathematical analyses of the effects of relative price elasticities in sequential markets from other papers are referenced; some mathematical analyses are developed in this paper that additionally consider time dynamics; and most interestingly a detailed dynamic simulation of day ahead, hour ahead, and intra hour market behavior under different scenarios is developed and used to explore these questions and illustrate interesting cases.

Broadly speaking there are a number of major conclusions from this body of work. First and foremost is that it is indeed theoretically and practically possible for DP resources at high penetration to adversely affect market stability under some conditions. Price oscillations can develop which are self sustaining. Under high penetrations, it is vital for market operations to understand DP behavior and price elasticity and to include this in the market clearing algorithms and results. Second, DDR can be a useful resource provided that the technical performance characteristics of DDR resources are matched to the market products they are supplying. Both DP and DDR can be problematic if this obvious principle is violated. Third, and perhaps surprising, is that Self Optimizing Customers operating autonomously in response to published Day Ahead prices can be destabilizing in the market and cause supply-demand mismatches as a result. A good argument can be made for getting SOC resources to be market participants with information exchange with the ISO and even bid submission and full market participation.

Theoretical Development

Economists are familiar with the "Cobweb Theorem" which explains how a sequential market clearing where the supply side clears prices against observed demand without knowing the effect of new prices on demand (or vice versa) can lead to divergence or convergence of market prices and demand-supply balance. (ADD REFERENCE AND FIGURE and figure description) This theorem appears to "fit" sequential electricity markets. If the market load forecast (a) does not consider price elasticity and (b) factors the deviation from the previous hour's forecast into the next hour load forecast – then the conditions are set for an illustration of the cobweb theorem. The market operator first over estimates load (because the actual load decreases in response to price) and then underestimates it (because reducing the next hour forecast due to the price-elastic load decrease the prior hour ignores the effect that lower prices will have). Depending upon the relative elasticities of supply and demand, this process can converge or diverge.

A more analytical exposition of these phenomena specific to energy markets was recently developed by researchers at MIT[1]. In this paper the supply and demand models in the sequential market are more general in description and the conditions for price stability are stated in terms of the relative convexity of the supply and demand curves.

Both the "generic" cobweb example (http://en.wikipedia.org/wiki/Cobweb_model) and the MIT paper deal with the mechanics of a sequential market in which the supply side adjusts (and the price adjusts) to meet the actual demand and then the demand adjusts to the new price. The supply side is unaware of the elastic behavior of the demand side.

In this paper we take a different tack – we develop a conceptual market framework as a physical dynamic system with simplified dynamic models of generation, demand, and market behavior. This system has three time constants thus three poles in its framework.

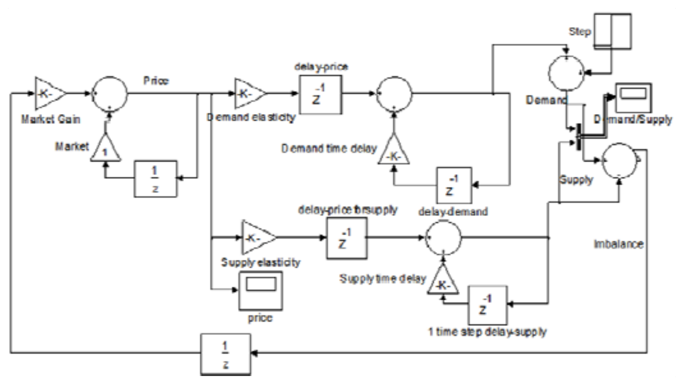

Figure 1: Impact of Dynamic on Stability

In this simple model, the supply side reacts to the price with a given elasticity (gain) and delay. (a time constant posed in the z-transform space.). The demand side also reacts to the price with a given elasticity (gain) and delay. The market operates to take the imbalance between demand and supply as inputs to a clearing function which adjusts the price according to the supply and demand elasticities as known (or not) to it – that is, its feedback gain is the inverse of the sum of the supply elasticity (assume to be perfectly known) and the demand

[1] On The Stability of Wholesale Electricity Markets under Real-Time Pricing

elasticity (which is known with some error.) and it has a delay which is the periodicity of the market clearing function. This model, while simple, catches the essence of the real time imbalance market or the hourly market with the time dynamics of the generation and the demand side response to new market signals.

The critical parameters in this system are the ratios of price elasticities between supply and demand, and the ratios for the three time delays involved on the supply, demand, and market processes. The relative magnitude of error in estimating demand elasticity in the market clearing is also critical. Thus there are five ratios overall that are of interest and for which we can analyze market stability. These are stated as:

- GL demand elasticity
- Gg = r*GL generation elasticity
- 1/(Gg+ GL'), GL'= GL+e*GL market gain with demand eleasticity error
- TL demand time constant
- Tg = g*TL generation time constant
- Tm= m*TL market time

Routh – Hurwitz criterion can be applied to the algebraic expressions for the poles of the system and the stability criteria plotted for differing values of the ratios above, as shown in Figures 2 - 4:

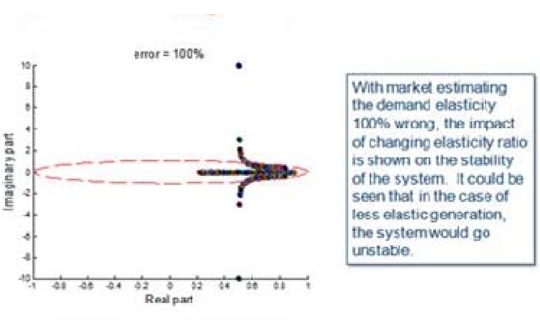

Figure 2: Stability Across Elasticity Ratio

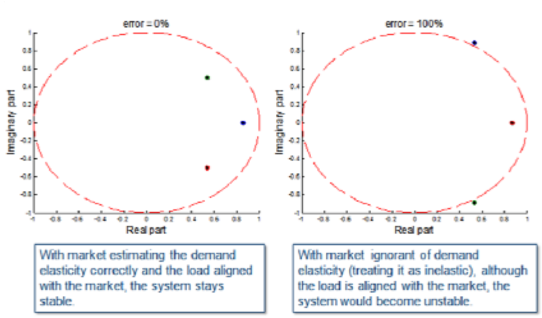

Figure 3: Impact of Including Demand Elasticity in the Market

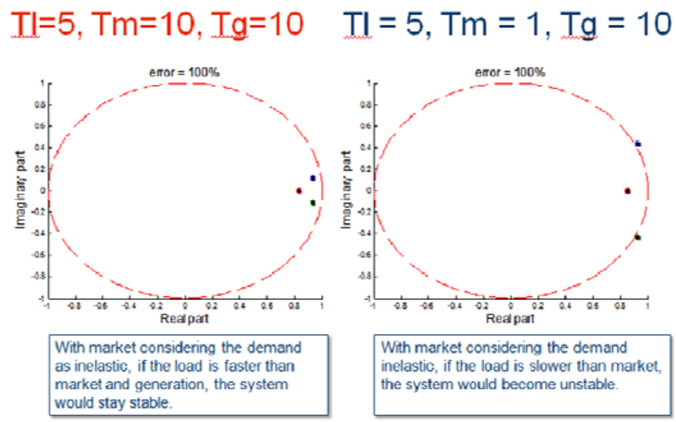

Figure 4:

The poles of the systems can be calculated for different values of these ratios and stability criteria applied. Figures 2 through 4 show some interesting results: First, if the time constants are aligned such that the generation is faster than the demand and the market, the system is always stable. Second, if that condition is not met, then for some ratios of generation and demand elasticity the system will become unstable. Third, if the market is "aware" of demand elasticity and factors this into the clearing, then the system is stable. The market stability is sensitive to the magnitude of error in estimating demand elasticity.

Thus a simple example that considers how the dynamic response of generation, demand, and market operations interact over ranges of relative elasticities and market information about demand elasticity demonstrates that there are definitely regions where the overall system will not be stable.

A Detailed Market Simulation

A detailed dynamic model of an ISO market operation was constructed. In this model, the Day Ahead (DA), Hour Ahead (HA), and intra Hour or Real Time Dispatch (RTD) markets are simulated. Each market uses non-linear supply curves representative of a real market with a real mix of generation as appropriate to each market time period. The DA market can schedule all types of resources while the HA market is restricted to units that can be committed and ramped on an hourly basis (such as some CCGT and most CT units) and the RTD market is limited to those units fast enough to follow real time dispatch. The demand curves are modeled as elasticities based on published analyses of demand elasticity adapted to different penetrations of DP for the purposes of this simulation.

Demand resources are modeled on an end use basis including lighting, HVAC, hot water heating, commercial refrigeration. The technical performance of each in terms of delays in information and control processing, response time,and duration are modeled. DDR in the market has to clear at prices similar to the generation at the margin in order to be scheduled or dispatched; therefore in the market clearing DDR can be modeled as a penetration in terms of % of generation. DDR and DP resources have "Payback" effects following a response – the load later in time may increase as thermal energy is restored or deferred action taken. This varies with end use and does not occur for all (lighting has no payback, for example)

The overall simulation was constructed in the paradigm of Business Dynamics using the system platform Vensim (Venatna Systems) in order to facilitate fast prototyping and easy study of multiple variations. An overall figure of the real time portion of the simulation is shown in Figure 5.

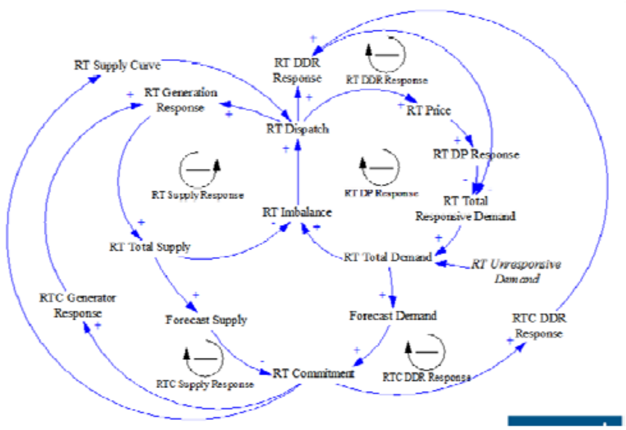

Figure 5: Portion of Market Dynamics Model

In this figure the generation and demand interaction overall in the three markets can be seen. The simulation lets us see the behavior of generation and load and prices dynamically in the time periods of the three different markets, as well as exploring possibilities if DDR or DP is used or responds in the different markets / price signals. The total model is too complex to show it in all details here. It is unusual in that (a) it integrates the day ahead, hour ahead, and real time market processes and (b) includes the physical time dynamics of both the supply and demand market elements.

There also is a model of an SOC in the day ahead market. This load resource (in aggregate) sets its hourly schedule after the DA prices have cleared. It is thus a complex kind of DP which is shifting load forward and backward in time. The SOC has thermal storage, electric storage, local distributed generation, and the ability to reduce demand. It controls these resources to minimize its total energy costs while maintaining comfort levels within parameters during the day – thus it may "pre-cool" in the early morning hours and then adjust HVAC load according to local PV production and energy prices during the day. An example of SOC component behavior and total profile is shown in Figure.6

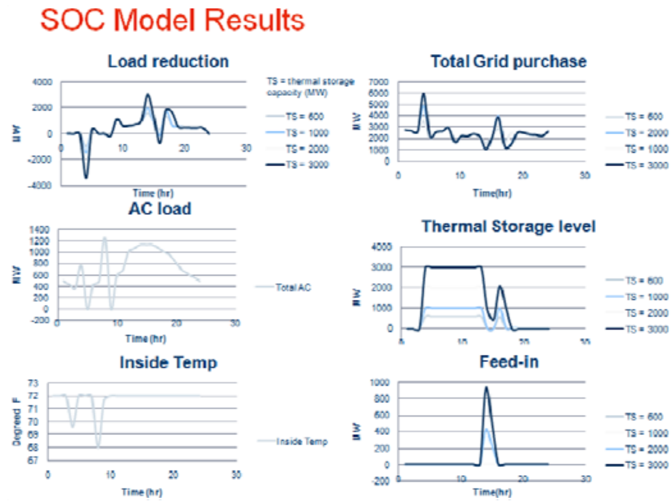

Figure 6: SOC Profiles

Simulation Results

Figure 7 shows simulation results for a case where the load is assumed to be reacting to HA prices and where the demand price response continues until the next HA prices are published – so that the market clearing "sees" the current hour's demand reaction to that hour's price. In this case the market is unstable as predicted by the various theoretical models.

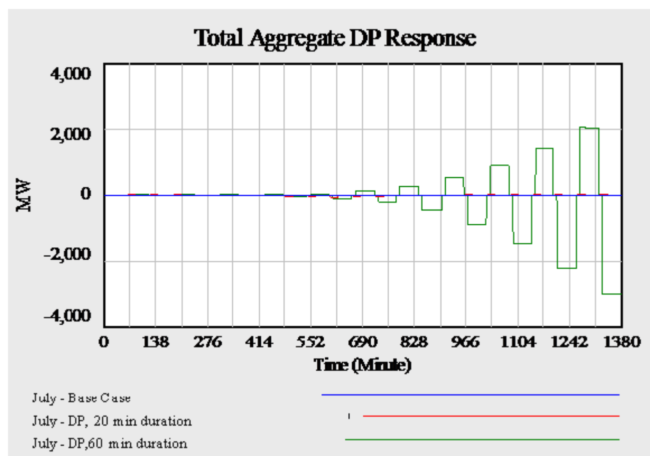

Figure 7: Dynamic Pricing in the Markets

Figure 8 shows the same case but with different penetrations of Dynamic Pricing – which translates to different overall elasticities. One interesting aspect of these simulations is that the instability definitely "begins" near the daily peak load as prices and demand are not great enough to enter an unstable regime before that, but once started it may persist or be damped in later hours depending upon how the elasticity changes post the peak hour.

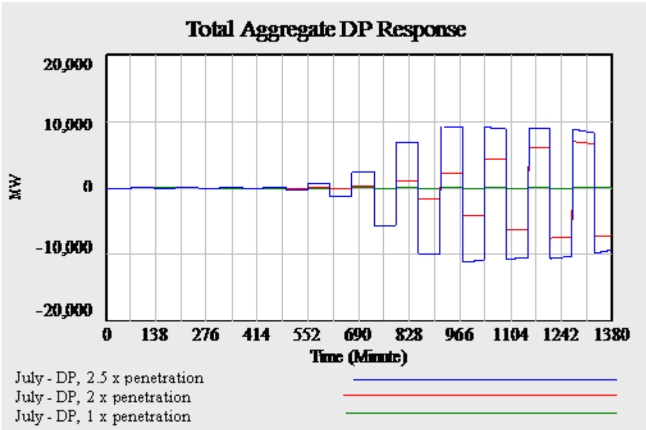

Figure 8: Dynamic Pricing Penetrations

When the market clearing includes an estimate of demand elasticity but that estimate is in error, instabilities may also arise as shown in Figure 9 below.

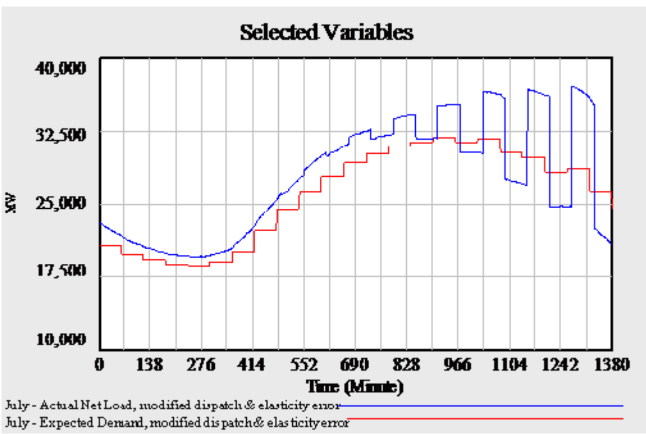

Figure 9: DP Elasticity Estimation

If demand is reacting to the RT market ("RTD" prices) but has a duration of its response greater than the market periodicity – i.e. until the next price is published – then similar behaviors can be seen in the RTD prices. In this case the price changes every 5 minutes and the load is responding with durations of 5, 10, or 20 minutes – the latter cases are unstable.

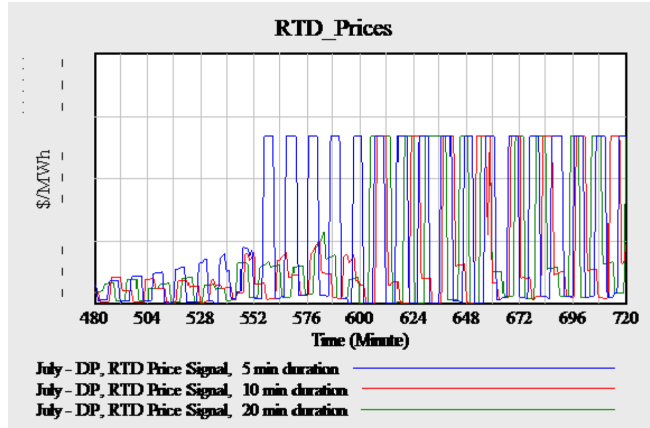

Figure 10: Dyanamic Pricing in Real Time Markets

Relatively small amounts of Self Optimizing Customer (SOC) load in the markets (400 MW in this example) can also cause price instability as shown in Figure 11. In this case the system is stable even with high (170% of nominal) dynamic pricing penetration but a small addition of SOC penetration causes instability.

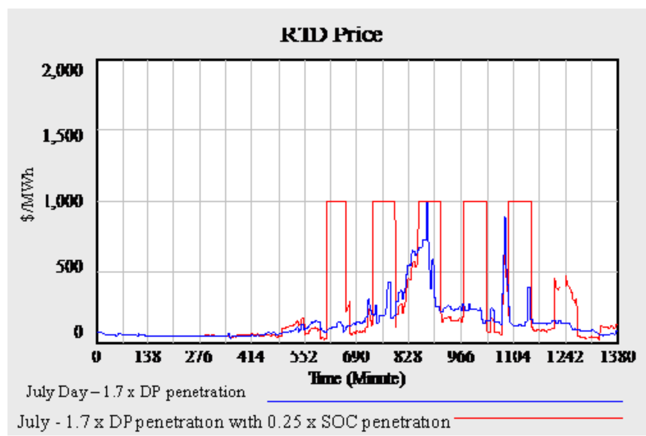

Figure 11: Impact of Self Optimizing Customers

By comparison, inclusion of Dispatchable Demand Response in the markets (DDR) is always stable provided that its time dynamics are matched to the market periodicity in which it participates. Here a DDR with sub-hourly duration introduces some generation volatility in response; a longer – 60 minute – duration is quite well behaved in the hour ahead markets. This is because the market anticipates the DDR response (and in this simulation also the duration and kick back effects) to dispatch instructions.

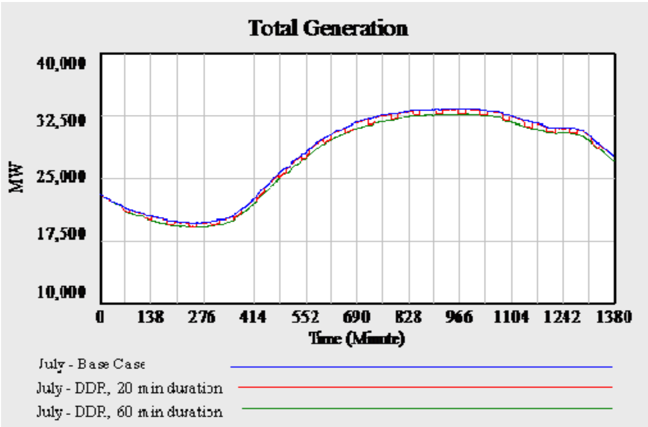

Figure 12: Impact of of Dispatchable DR

Discussion of Simplifications and Possible Refinements

The market clearing and generation dynamics are simplified in that start-up costs and start up times are not represented; the market clearing is a representation of a simple dispatch using a supply curve. Generators are modeled in aggregate, not individually. In this regard the model is simpler and probably optimistic as compared to a true production cost simulation that modeled all the "real" market models and mathematics in high fidelity. Integrating the dynamic demand side models into a production cost simulation is a feasible forward research activity although some of the demand models are not easily captured in a "market" simulation that only includes the optimization codes and constraints and not the time dynamic behaviors.

One important theoretic result of the process control model of the market dynamics is that if the generation is "slower" than the load response then instability can occur. That phenomenon was not exhibited in the larger simulation because the generation classes participating in the various markets were already selected on the basis of their ability to respond. That is, the only units in the RT market are able to respond significantly in a 5 minute time frame and so on. This is nonetheless an ongoing point to keep in mind, as many autonomous demand side behaviors will be very "fast" by comparison with generation. Some end users can be switched on and off as fast as communications technologies will allow – hot water heaters and lighting, for instance.

The extent to which individual end use elements are aggregated is extreme and may exaggerate some effects. On the other hand, similar end uses responding to price signals will respond together as prices change, and many end users are in fact fairly homogenous in their dynamic behavior. The aggregation of the Self Optimizing customer is one area where reality would be more complex and considerable variation by customer class and configuration of behind the meter resources are to be expected. The simulation could be enhanced to have multiple SOC models.

One key future demand resource that was not represented is Electric Vehicles. These could have significant market impacts and depending upon how they are integrated, could look like a DDR, a DP, or a complex SOC resource in aggregate. This is a research question worth exploring.

Only the energy markets were considered. The use of demand resources in the ancillaries markets was not modeled. However, we note that visibility and market information (i.e. bid input) is mandatory for ancillaries provision and the technical performance of ancillaries provision is also specific and mandatory. Demand resources as ancillaries providers are unlikely to create disturbance in the markets so long as they meet these requirements.

Conclusions

It has been shown from a simplified theoretical perspective that some regimes of demand side integration into the markets; in particular the ability of consumers to automatically respond to price either in a real time sense or in response to day ahead prices, can be unstable or undesirable. The theory and the detailed simulation both bear this out qualitatively and to some extent quantitatively. Additionally, the correct alignment of demand side resources with market products in terms of technical performance, is critical to market behavior and stable results.

Several states are exploring or have already committed to high levels of DP participation, and many microgrids are in the planning stages. Thus the conclusions about incorporating information around these interactions in the markets are quite cogent. ISOs should begin to think about how they will integrate demand elasticity into their market clearing algorithms and load forecasting, and how they will estimate demand elasticity on an ongoing basis. As this will be critical to market pricing, how the ISOs also achieve transparency in the elasticity estimation process is going to become an additional challenge.

Self optimizing customers present a related challenge. The potential for multiple SOC networksto destabilize the markets is real. It may not be realistic to require SOC's to bid into the market as conventional resources, given the time shifting nature of their operations. Factoring SOCs into the market clearing will become critical, either via a bid offer process that leads to known schedules or via a complex cross-elasticity process integrated with microgrid load and production forecasting. Either one requires the ISO to have model information of individual microgrid behavior.

References

1. On The Stability of Wholesale Electricity Markets under Real-Time Pricing

2. http://en.wikipedia.org/wiki/Cobweb_model